

# ON THE PROGENITOR AND SUPERNOVA OF THE SN 2002CX-LIKE SUPERNOVA 2008GE<sup>1,2</sup>

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## ABSTRACT

We present observations of supernova (SN) 2008ge, which is spectroscopically similar to the peculiar SN 2002cx, and its pre-explosion site that indicate that its progenitor was probably a white dwarf. NGC 1527, the host galaxy of SN 2008ge, is an S0 galaxy with no evidence of star formation or massive stars. Astrometrically matching late-time imaging of SN 2008ge to pre-explosion *HST* imaging, we constrain the luminosity of the progenitor star. Since SN 2008ge has no indication of hydrogen or helium in its spectrum, its progenitor must have lost its outer layers before exploding, requiring that it be a white dwarf, a Wolf-Rayet star, or a lower-mass star in a binary system. Observations of the host galaxy show no signs of individual massive stars, star clusters, or H II regions at the SN position or anywhere else, making a Wolf-Rayet progenitor unlikely. Late-time spectroscopy of SN 2008ge show strong [Fe II] lines with large velocity widths compared to other members of this class at similar epochs. These previously unseen features indicate that a significant amount of the SN ejecta is Fe (presumably the result of radioactive decay of <sup>56</sup>Ni generated in the SN), further supporting a thermonuclear explosion. Placing the observations of SN 2008ge in the context of observations of other objects in the class of SN, we suggest that the progenitor was most likely a white dwarf.

*Subject headings:* astrometry — stars: evolution — supernovae: general — supernovae: individual (SN 2008ge)

## 1. INTRODUCTION

In the last decade, a new class of supernovae (SNe) has been discovered. The class, named after its first member, SN 2002cx (Li et al. 2003), has several observational similarities to typical SNe Ia, but also has several distinguishing properties: low luminosity for its light-curve shape (e.g., Li et al. 2003), a lack of a second maximum in the NIR bands (e.g., Li et al. 2003), low photospheric velocities (e.g., Li et al. 2003), late-time spectra dominated by narrow permitted Fe II (e.g., Jha et al. 2006), and a host-galaxy morphology distribution highly skewed to late-type galaxies (Foley et al. 2009; hereafter F09; Valenti et al. 2009). Additionally, a single member of the class, SN 2007J, displays strong He I in its spectrum (F09).

A recent member of this class, SN 2008ha, had both a very low photospheric velocity at maximum brightness

(about 4000 km s<sup>-1</sup>; Foley et al. 2010a) and extremely low luminosity ( $M_V = -14.2$  mag at maximum brightness; F09; Valenti et al. 2009). The observations of this SN are difficult to match to conventional SN models. Valenti et al. (2009) suggested that SN 2008ha (and possibly all SN 2002cx-like objects) had massive progenitors, while F09 explored both massive-star progenitor models and models that involved a white dwarf (WD) progenitor. The light curves and velocities of SN 2008ha can be matched by a model of a 13 $M_\odot$  main-sequence mass CO star undergoing a significant amount of fallback (Moriya et al. 2010); however, stars with a main-sequence mass of  $M \lesssim 25M_\odot$  are not expected to undergo fallback (Fryer 1999). The maximum-light spectrum of SN 2008ha suggested that C/O burning occurred during the explosion, pointing further to a WD progenitor (Foley et al. 2010a).

The best way to determine the progenitor system for these events would be to unambiguously detect the progenitor (or donor) star of a SN in pre-explosion imaging. This technique has been very successful at detecting nearby core-collapse SN progenitors (see Smartt 2009, for a review), but has rarely been attempted for SNe Ia (Maoz & Mannucci 2008; Nelemans et al. 2008). For this type of study, the following data are required: a high-resolution (to separate individual stars), relatively deep (to detect the progenitor star) pre-explosion image of the SN site and a SN image that is deep enough to have good detections of several stars in common with the pre-explosion image. A relative astrometric solution is obtained for the two images, and then the SN position can be precisely determined on the pre-explosion image. Potential progenitor stars can then be identified and their properties studied, or alternatively if no stars are consistent with the SN position, limits can be placed on the

<sup>1</sup> This paper includes data gathered with the 6.5 meter Magellan telescope at Las Campanas Observatory, Chile.

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properties of the progenitor star. With the appropriate observations, one can place interesting constraints on the progenitor properties of SN 2002cx-like SNe.

SN 2008ge was discovered by the CHilean Automated Supernova sEarch CHASE (Pignata et al. 2009) on 2008 October 8.27 (UT dates are used throughout this paper) at mag 12.8 (Pignata et al. 2008b) in NGC 1527, an S0 galaxy with a recession velocity of  $1212 \text{ km s}^{-1}$ . Using the surface brightness fluctuation method, Tonry et al. (2001) determined that the distance modulus for NGC 1527 is  $\mu = 31.28 \pm 0.22 \text{ mag}$ . Using the new Cepheid zero point of Freedman et al. (2001), this corresponds to a corrected distance modulus of  $\mu = 31.12 \pm 0.22 \text{ mag}$ , which we will adopt as the distance modulus for SN 2008ge.

Despite discovering SN 2008ge on 2008 October 8.27, Pignata et al. (2008b) also report detecting SN 2008ge on previous images, with the earliest detection on 2008 September 8.23 (at mag 12.4) and the last non-detection on 2008 August 21.24. Our light curve (presented in Section 2.2) shows that SN 2008ge peaked in  $V$  around 2008 September 17.

We determined from a spectrum obtained on 2008 October 15 that SN 2008ge was similar to the peculiar SN 2002cx 23 d past maximum brightness (Stritzinger et al. 2008). This is consistent with our  $V$ -band phase of 28 d on that date. Given the sparse pre-maximum data, the rise time should be between 9 – 27 d.

NGC 1527 has been twice imaged by *HST* before the detection of SN 2008ge. In this paper, we present observations of SN 2008ge and its host galaxy, determine the properties of potential progenitor stars at the location of SN 2008ge, and examine the implications of those properties in the context of the progenitors for SN 2002cx-like objects.

## 2. OBSERVATIONS AND DATA REDUCTION

### 2.1. Identification and *HST* Photometry of the Progenitor Site

NGC 1527 was observed with *HST*/WFPC1 on 1993 October 20 (Program 4904; PI Illingworth) and *HST*/WFPC2 on 1995 January 6 (Program 5446; PI Illingworth). The WFPC1 observation was a single 300 s exposure with the F555W (roughly  $V$ ) filter, while the WFPC2 observation included two exposures of 80 s each with the F606W (a broad  $V$ ) filter.

To determine whether the progenitor of SN 2008ge is detected in the archival *HST* observations, we performed differential astrometry using optical observations of the SN. Observations of SN 2008ge were obtained with LDSS3<sup>11</sup> with the Magellan Clay telescope on 2009 October 16. The images were reduced using the SMSN pipeline as described in Rest et al. (2005) and Miknaitis et al. (2007).

The astrometry was performed with the IRAF<sup>12</sup> tasks *geomap* and *geotran* using 29 objects in common with the *HST*/WFPC2 images resulting in an astrometric rms

of  $\sigma_{\text{LDSS3} \rightarrow \text{HST}} = 45 \text{ mas}$  in each coordinate. The same procedure was performed with the *HST*/WFPC1 images, which despite its smaller field of view, and therefore only 5 stars in common, we obtained an astrometric rms of  $\sigma_{\text{GB} \rightarrow \text{HST}} = 20 \text{ mas}$ .

The SN is very close to the bright nucleus of NGC 1527. At the time of our Magellan observation, it had faded to the point where it was difficult to directly measure its position. To provide an accurate SN position, we subtracted the south-west section of the galaxy from the north-east section of the galaxy (rotated and flipped about the galaxy center), producing a relatively clean difference image (shown in Figure 1). The SN is clearly detected in our stacked photometry with position  $(\alpha, \delta) = (04:08:24.689, -47:53:47.01)$ , with the absolute astrometry set using 2MASS. This position is consistent with that determined from our Gemini acquisition images (when the SN was significantly brighter; see Section 2.3). The depth of the LDSS3 images make them preferable for determining an astrometric solution.

The position of SN 2008ge on the archival *HST* images are shown in Figure 1. In both cases, we find no clear progenitor coincident with objects in the archival *HST* images. The WFPC2 image is 0.45 mag deeper than the WFPC1 image, and the filters are very similar. Therefore, for the remainder of this study, we focus on the WFPC2 image.

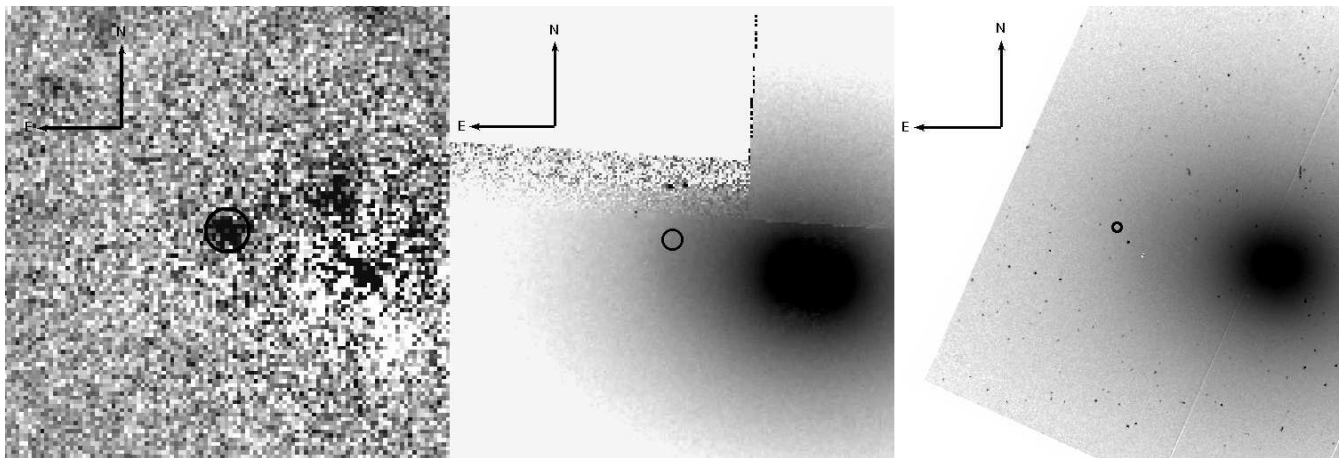
Since no progenitor star was detected, we can use the *HST*/WFPC2 image to place limits on the brightness of the progenitor. The surface-brightness profile is extremely smooth, and we expect that any bright star would be easily detected. Using *dophot*, we were able to detect nearly all astrophysical objects to a signal-to-noise ratio ( $S/N$ ) of  $\sim 3$  with few false detections. To determine the exact limit, we placed artificial stars with varying brightnesses in the image. We then ran *dophot* on that image to recover the artificial stars. We find that at the SN position and positions with similar backgrounds that we recover  $> 90\%$  of all objects to  $S/N = 3$ . We then calculated the brightness that would yield a particular  $S/N$ . For  $S/N = 3$  (5), we have a limiting magnitude of  $m_{\text{F606W}} = 24.3 \text{ mag}$  (23.2 mag); at our adopted distance (and assuming no host-galaxy extinction), this corresponds to  $M_V = -6.7 \text{ mag}$  ( $-7.8 \text{ mag}$ ).

### 2.2. Supernova Photometry

Photometry of SN 2008ge was obtained by the 0.41 m Panchromatic Robotic Optical Monitoring and Polarimetry Telescope (PROMPT Reichart et al. 2005) in the Luminance filter, which is a passband filter with wavelength range from  $\sim 4000$  to  $\sim 7000 \text{ \AA}$ . Instrumental magnitudes were measured using the template subtraction technique with a code based on the ISIS package (Alard & Lupton 1998; Alard 2000). For calibrating the instrumental magnitudes to the  $V$  band we used the S-correction technique (Stritzinger et al. 2002), but following the prescription of Pignata et al. (2008a). We convert to the  $V$  band because its effective wavelength is closest to the Luminance filter. Since the spectroscopic follow up began around 20 days after maximum light, to correct the early photometric points we used the spectra of SN 2005hk (Phillips et al. 2007). The two objects are both spectroscopically similar to SN 2002cx at later times (see Figure 4) and the correction agrees quite well for the phases

<sup>11</sup> <http://www.lco.cl/telescopes-information/magellan/instruments-1/ldss-3-1/>.

<sup>12</sup> IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.



**Figure 1.** LDSS3 *r*-band (left), *HST*/WFPC2 F606W (center) and *HST*/WFPC F555W (right) images at the position of SN 2008ge obtained 1 year after and 13 and 15 years before explosion, respectively. The images are  $20'' \times 20''$ , and North is up and East is left. The LDSS3, *HST*/WFPC, and *HST*/WFPC2 images have a pixel scale of 0.188, 0.044, and  $0.1'' \text{ pixel}^{-1}$ , respectively. The LDSS3 image has been flipped about the center of the host galaxy and subtracted from the original image to create a difference image. The position of SN 2008ge is marked by the black circles whose radius corresponds to  $1''$  for the LDSS3 image and  $10\sigma$  uncertainty in the position for the *HST* images.

where the spectroscopic sequences overlap. This makes us confident that the early-time corrections are appropriate.

We present our *V*-band light curve of SN 2008ge in Table 1 and Figure 2. The SN peaked at  $V \approx 13.8$  mag on or around 2008 September 17. It is worth noting that SN 2005hk, which had very well sampled light curves, peaked in *V* 3.6 d after peaking in *B* (Phillips et al. 2007). At our adopted distance modulus (and assuming no host-galaxy extinction; see Section 2.3), SN 2008ge peaked at  $M_V \approx -17.4$  mag (with a total uncertainty of  $\sim 0.2$ – $0.3$  mag), comparable to SNe 2002cx ( $M_V = -17.49$  mag) and 2005hk ( $M_V = -18.08$  mag; Phillips et al. 2007). SN 2008ge declines slower than either SN 2002cx or SN 2005hk in *V*. SN 2008ge has  $\Delta m_{15}(V) \approx 0.34$  mag (the relatively large photometric uncertainty and single data point before maximum propagates to a large uncertainty in the measurement), which is much smaller than the measured value for either SN 2002cx ( $0.95 \pm 0.06$  mag) or 2005hk ( $0.83 \pm 0.05$  mag). We caution that our *V* band may still be slightly contaminated by the *R* band, and could partially explain the width of the *V*-band light curve.

### 2.3. Spectroscopy

Seven low-resolution spectra of SN 2008ge were obtained at the Las Campanas Observatory with the Boller & Chivens spectrograph<sup>13</sup> on the 2.5 m du Pont telescope, the IMACS spectrograph (Dressler et al. 2006) on the Magellan Baade 6.5 m telescope, and the LDSS3 spectrograph on the Magellan Clay 6.5 m telescope. An additional three spectra were also procured with the GMOS spectrograph (Hook et al. 2005) on the 8 m Gemini-South telescope. A single high-resolution ( $R \approx 30,000$ ) spectrum was obtained with the MIKE spectrograph (Bernstein et al. 2003) on the Magellan Clay 6.5 m telescope. A journal of observations is provided in Ta-

**Table 1**  
CHASE *V*-Band  
Photometry of  
SN 2008ge

JD	$V^a$ (mag)
2454717.7	13.95 (06)
2454726.4	13.82 (12)
2454734.8	13.91 (08)
2454741.7	14.08 (06)
2454747.8	14.40 (05)
2454754.7	14.66 (06)
2454760.6	14.84 (07)
2454781.6	15.23 (05)
2454787.6	15.34 (06)
2454800.7	15.53 (07)
2454817.6	15.92 (06)
2454838.6	16.48 (08)
2454842.6	16.45 (07)
2454847.6	16.54 (08)

**Note.** — Uncertainties (units of 0.01 mag) are given in parentheses.

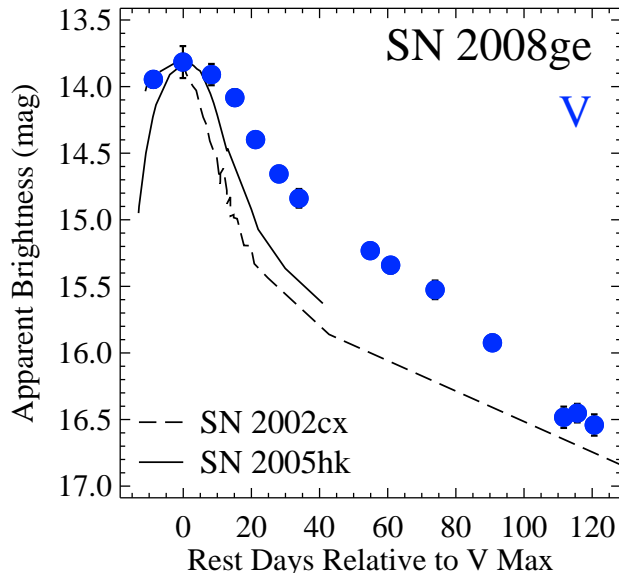
<sup>a</sup> *V*-band measurements are transformed from observations observed in the Luminance filter.

ble 2.

Standard two-dimensional image processing and spectrum extraction was accomplished with IRAF. Low-order polynomial fits to calibration-lamp spectra were derived from night-sky lines in the object frames were applied. Flux calibration was applied to the extracted spectra using observations of spectrophotometric standards usually observed during the same night as the SN. Telluric features were removed from all of the spectra taken at Las Campanas using high S/N spectra of telluric standards. Telluric corrections were not performed on the Gemini spectra.

The spectroscopic sequence of SN 2008ge is presented in Figure 3, and Figure 4 contains a comparison between SN 2008ge and SN 2002cx. Although the phases in our comparison are not perfectly matched, and some of

<sup>13</sup> <http://www.lco.cl/telescopes-information/lco/telescopes-information/irenee-du-pont/instruments/website/boller-chivens-spectrograph-manuals/boller-chivens-spectrograph-manuals>



**Figure 2.** V-band light curves of SNe 2002cx (dashed line), 2005hk (solid line), and 2008ge (blue points). The light curves of SNe 2002cx and 2005hk have been shifted to match the light curve of SN 2008ge at peak.

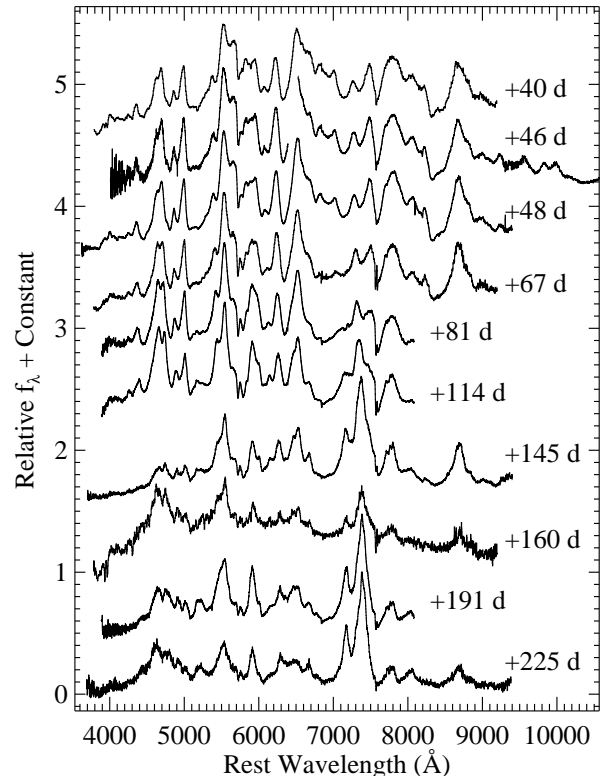
**Table 2**  
Log of Spectral Observations

Phase <sup>a</sup>	UT Date	Telescope / Instrument	Exposure (s)
40.4	2008 Oct. 27.3	du Pont/B&C	3 × 300
46.4	2008 Nov. 2.3	Baade/IMACS	300
48.3	2008 Nov. 4.2	Clay/MIKE	2 × 3600
48.3	2008 Nov. 4.2	Clay/LDSS3	300
67.4	2008 Nov. 23.3	du Pont/B&C	3 × 500
81.2	2008 Dec. 7.1	GS/GMOS	3 × 400
114.2	2009 Jan. 9.1	GS/GMOS	3 × 600
145.2	2009 Feb. 9.1	Clay/LDSS3	3 × 600
160.2	2009 Feb. 24.1	du Pont/B&C	3 × 600
192.1	2009 Mar. 28.0	GS/GMOS	2400
225.1	2009 Apr. 30.0	Clay/LDSS3	1800

<sup>a</sup> Days since V maximum, 2008 Sep. 16.9 (JD 2,454,726.4).

the features appear to be slightly broader in SN 2008ge, the strong resemblance between the two objects is irrefutable. The first spectrum of SN 2008ge is dominated by Fe-group elements, with additional strong lines from Na D and Ca II. We refer the reader to Branch et al. (2004), which performed a detailed study of the spectra of SN 2002cx.

No signatures of H $\alpha$  nor He I is found in the spectral series of SN 2008ge, indicating that the progenitor was likely an evolved star. Our high S/N, high-dispersion ( $R \approx 30,000$ ) MIKE spectrum of SN 2008ge shows a weak Na D absorption system from the Milky Way, but no evidence for Na D absorption or H $\alpha$  emission from the host galaxy. We measure a  $3\sigma$  upper limit of  $0.01 \text{ \AA}$  for the equivalent width of the Na D2 lines suggesting that there is little to no host-galaxy extinction. There is also no sign of star formation at the position of the SN nor any significant amount of hydrogen in the circumstellar environment.



**Figure 3.** Optical spectra of SNe 2008ge. Phases relative to maximum brightness are marked.

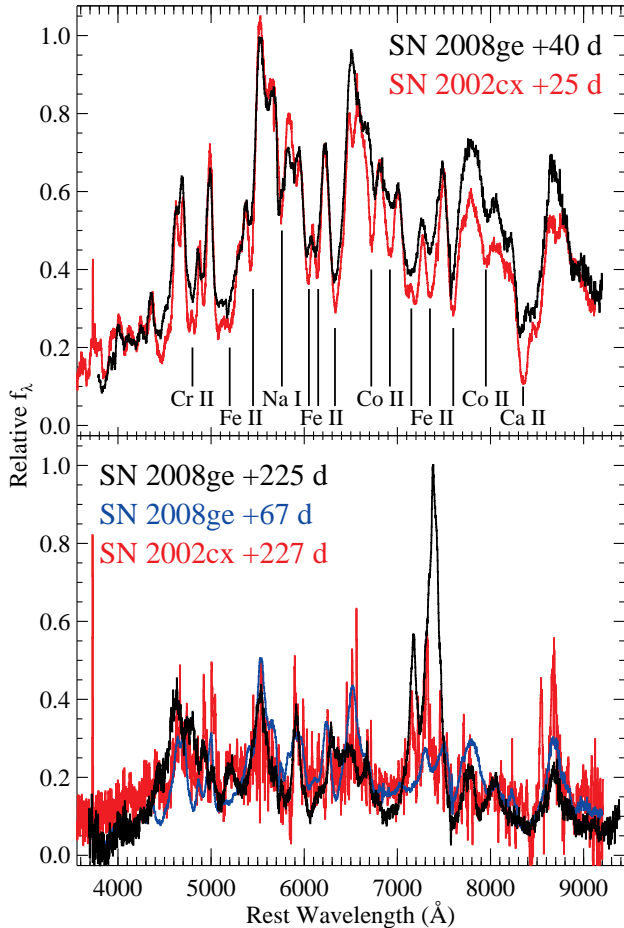
NGC 1527 is undetected in IRAS, with relatively strict limits of  $< 0.1 \text{ Jy}$  in each band (Knapp et al. 1989). Using the Kewley et al. (2002) relationship between IRAS emission and star-formation rate (SFR), we place a limit on the SFR of  $< 7.2 \times 10^{-3} M_{\odot} \text{ year}^{-1}$ . Additionally, NGC 1527 is not detected in H I 21 cm with a flux limit of  $< 1.56 \times 10^{-5} \text{ Jy}$  (Huchtmeier 1989). Both of these observations place significant constraints on the SFR of the host galaxy.

### 3. RESULTS

#### 3.1. Limits on Progenitor System

In Figure 5, we present the non-rotating standard mass-loss evolutionary tracks for stars with  $Z = 0.001$  and  $0.1$  (corresponding to  $0.05$  and  $5Z/Z_{\odot}$ , respectively) of the Geneva group (Lejeune & Schaerer 2001). We compare these tracks to the upper limit of  $M_V = -6.7 \text{ mag}$  for the progenitor of SN 2008ge. Only knowing the limit of the luminosity in a single band, we can place limits on the initial mass of the progenitor and possible binary companion. If any star in the progenitor system was still on the main sequence and had low metallicity, then its initial mass is  $M_{\text{init}} \lesssim 85 M_{\odot}$ . For high metallicity, the limit is lower with  $M_{\text{init}} \lesssim 60 M_{\odot}$ . If the progenitor was on the horizontal or red-giant branch, then there are stricter limits of  $M_{\text{init}} \lesssim 12 M_{\odot}$  for both the low and high metallicity cases.

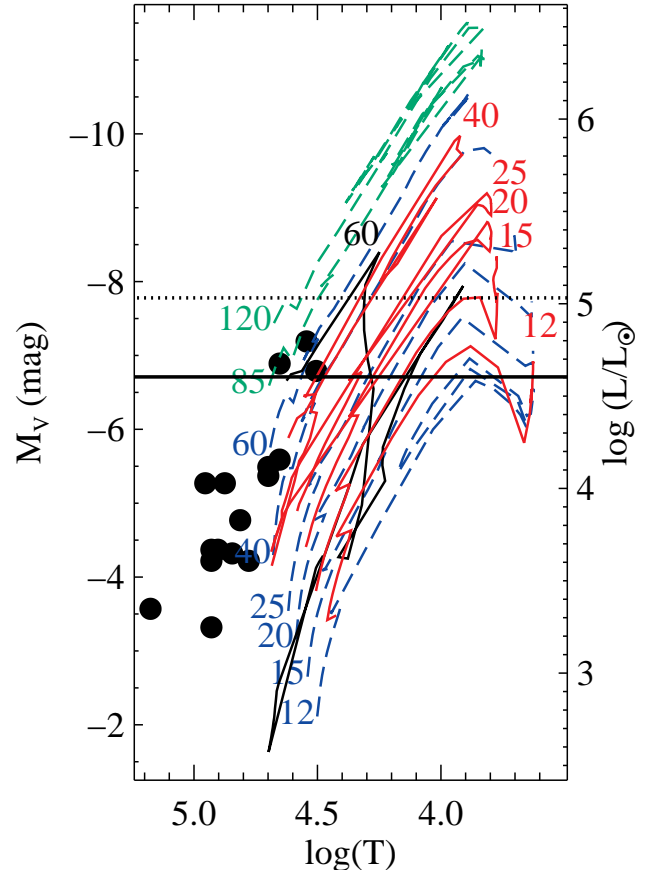
As discussed in Section 2.3, there is no indication of hydrogen in the spectrum of SN 2008ge, so the progenitor star was almost certainly not on the main sequence, horizontal branch, or red-giant branch star (although



**Figure 4.** Spectra of SN 2008ge at +40 (black; top panel), +67 (blue; bottom panel), and +225 d (black; bottom panel) relative to  $V$  maximum. Comparison spectra of SN 2002cx (+25 and +227 d relative to  $B$  maximum in the top and bottom panels, respectively) are shown in red. For the well-sampled SN 2005hk, its light curves peaked in  $V$  3.6 d after  $B$  (Phillips et al. 2007). Line identifications from Branch et al. (2004) have been marked.

a potential binary companion could be). In Figure 5, we also plot example Wolf-Rayet stars (Crowther 2007). The most luminous of these stars, which correspond to late-type WN Wolf-Rayet stars, are ruled out by our  $3\sigma$  limit. However, earlier WN and WC/WO stars can not be directly ruled out by the current observations.

NGC 1527 is an S0 galaxy with no indication of star formation in its spectrum, no indication of a dust lane or other star formation (Phillips et al. 1996; Figure 1), and no detection from *IRAS* or in H I, placing strong constraints on the SFR of  $< 7.2 \times 10^{-3} M_{\odot} \text{ year}^{-1}$ . Fitting a single-stellar population (Jimenez et al. 2003) to the host-galaxy spectrum (obtained at the same time as the SN spectrum), we find a good fit with a single 9.5 Gyr population (see Foley et al. 2010b for details of the fitting). Additionally, there is no indication of any emission lines in the host-galaxy spectrum, placing strong constraints on the presence of massive stars or star clusters. All evidence indicates that there is not any significant population of massive stars in NGC 1527. The surface-brightness profile is extremely smooth, giving further evidence of a lack of individual massive stars or star clusters



**Figure 5.** Temperature-Magnitude diagram displaying the Geneva group stellar evolution tracks (Lejeune & Schaerer 2001) for  $Z = 0.001$  (dashed curves) and  $0.1$  (solid curves). The initial mass for each track is labeled. The black and green curves represent initial masses that are consistent with our magnitude limit if the star exploded on the main sequence. The blue and red curves represent initial masses that are consistent with our magnitude limit if the star exploded on the main sequence or at a later stage of evolution. The black dots represent Wolf-Rayet stars (Crowther 2007) corrected from  $v$  to  $V$  using the relationship of Breysacher (1986). The black solid (dotted) horizontal line represents our  $3\sigma$  ( $5\sigma$ ) limiting magnitude for the progenitor of SN 2008ge.

in the galaxy. For a star brighter than our detection limit to be masked by the galaxy, there would need to be large fluctuations to the surface-brightness profile, which do not exist.

### 3.2. Unique Phase Spectroscopy

Very few SN 2002cx-like objects have had their spectra published, and only SNe 2002cx (Li et al. 2003), 2005hk (Phillips et al. 2007; Sahu et al. 2008), 2007qd (McClelland et al. 2010) and 2008ha (F09; Foley et al. 2010a; Valenti et al. 2009) have had their light curves published. As a result, only these four objects have spectra with phase information. Li et al. (2003) published spectra with phases ranging from  $-4$  to  $+56$  d relative to  $B$  maximum. Jha et al. (2006) presented spectra of SN 2002cx at  $+227$  and  $+277$  d relative to  $B$  maximum. Phillips et al. (2007) presented spectra of SN 2005hk that covered  $-8$  to  $+67$  d relative to  $B$  maximum while Sahu et al. (2008) extended the spectroscopic coverage by presenting spectra at  $+228$  and



+377 d. SN 2007qd only has four published spectra with the earliest and latest being at +3 and +15 d, respectively. Although SN 2008ha had some spectroscopic differences from SNe 2002cx and 2005hk, spectra ranging from  $-1$  to  $+65$  d relative to  $B$  maximum have also been published (F09; Foley et al. 2010a; Valenti et al. 2009). However, no spectra of this class have been published that cover the phases 68 – 226 d relative to  $B$  maximum.

Our spectroscopic coverage of SN 2008ge fills in this gap with 6 spectra in this range. As seen in Figure 3, during this time the spectra remain relatively similar. This is not unexpected since the spectra of SN 2002cx at +56 and +227 d were very similar to each other except for the line widths (Jha et al. 2006). The main change in the spectral evolution of SN 2008ge is that the feature at  $\sim 7300$  Å (which we identify as [Fe II]; see Section 3.3) increases in strength with time.

Although it is important to see a SN 2002cx-like object transition from early to late times, SN 2008ge may not behave in a typical manner for this class. Unlike SNe 2002cx and 2005hk, the widths of the features do not significantly decrease (to separate into narrow, primarily Fe II, features) in SN 2008ge with time.

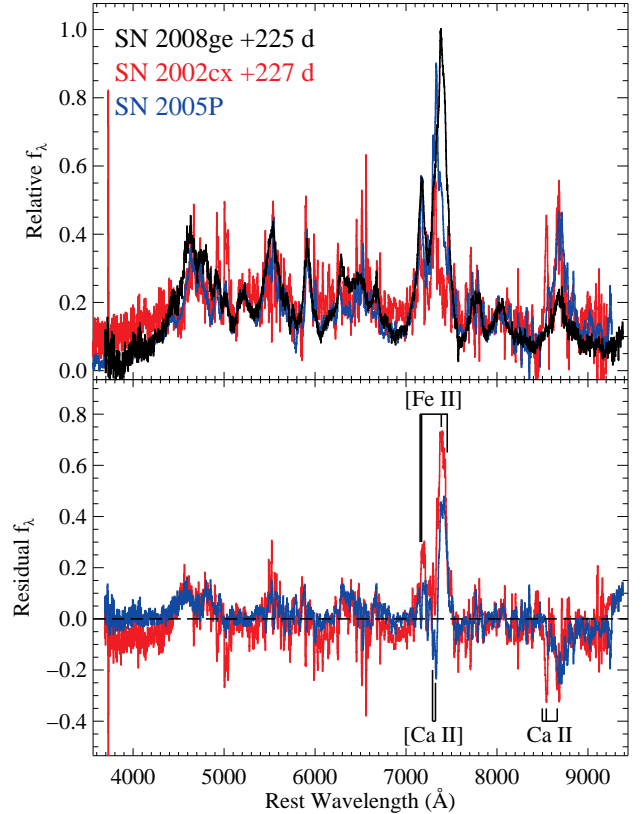
### 3.3. Late-Time Spectroscopy

At late times, the spectra of SNe 2002cx and 2005hk were dominated by permitted Fe II lines, with additional features from Na I, Ca II, [Ca II], and possibly [O I] (Jha et al. 2006; Sahu et al. 2008). Jha et al. (2006) and Sahu et al. (2008) both suggested that these objects may have emission from [Fe II]  $\lambda\lambda 7155, 7453$ , but alternatively considered the bluer feature being from O I  $\lambda 7157$ .

The 225 d spectrum of SN 2008ge is similar to SN 2002cx at  $t = 227$  d (see Figure 4), but SN 2008ge has much broader lines. SNe 2002cx and 2005hk had extremely low-velocity features ( $\sim 500$  km s $^{-1}$ ) at these late times. Clearly, SN 2008ge does not share this characteristic. Fitting a Gaussian to the relatively isolated feature at 5900 Å, which is likely Na D (but could possibly be [Co III]  $\lambda 5890$ ; Kuchner et al. 1994), we find a FWHM of 4300 km s $^{-1}$ .

In addition to the line widths, the main difference between the late-time spectra of SNe 2002cx and 2008ge is the strong emission near 7300 Å for SN 2008ge. One might expect this to be [Ca II]  $\lambda\lambda 7291, 7324$  since this is one of the strongest features in the late-time spectra of SNe 2002cx (Jha et al. 2006), 2005hk (Sahu et al. 2008), and SN 2008ha (F09). However, subtle differences in the wavelengths of these features require additional investigation.

By scaling the continua of the late-time spectra of SNe 2002cx and 2008ge, one can then subtract the SN 2002cx spectrum from the SN 2008ge spectrum to obtain a residual spectrum. This spectrum is presented in the bottom panel of Figure 6. As expected, the largest residuals occur at the previously mentioned feature. However, in the residual spectrum, it is clear that this feature is not consistent with [Ca II]  $\lambda\lambda 7291, 7324$ . There are two peaks at about 7185 Å and 7395 Å. We interpret these features as coming from [Fe II]  $\lambda\lambda 7155, 7171, 7388, 7453$ . It is also possible there is some emission from [Ni II]  $\lambda 7378$ . The exact centers of these lines are difficult to measure since the relative strengths of



**Figure 6.** *Top panel:* Late-time spectra of SNe 2002cx (red;  $t = 227$  d; Jha et al. 2006), 2005P (blue; Jha et al. 2006), and 2008ge (black;  $t = 220$  d). The SN 2005P spectrum was obtained on 2005 May 11, but no light curve has been published for this object. *Bottom panel:* Residual spectra created by subtracting the spectra of SNe 2002cx and 2005P from SN 2008ge (red and blue curves, respectively). The strong residuals corresponding to [Fe II]  $\lambda\lambda 7155, 7171, 7388, 7453$ ; [Ca II]  $\lambda\lambda 7291, 7324$ ; and Ca II NIR triplet are marked.

additional underlying lines in the spectra of SNe 2002cx and 2008ge may be different. In addition to the positive residuals from [Fe II], there is a strong negative residual from the Ca II NIR triplet.

Since the line widths of SNe 2002cx and 2008ge are very different at these times, we also compare SN 2008ge to another member of the class, SN 2005P. No light curves of SN 2005P have been published, so the phase information is not precise. SN 2005P was discovered on 2005 Jan 21 by Burket & Li (2005) with the last non-detection from 2004 July 8. A spectrum obtained on 2005 May 11 and presented by Jha et al. (2006) is reproduced in Figure 6. Assuming that SN 2005P peaked at most 10 d after discovery, the spectrum has a phase of  $100 \leq t \leq 307$  d. Although the phase of the spectrum might not be perfectly consistent with that of SN 2008ge, it is somewhat similar (and presumably it did not evolve quickly at these late times).

The spectra of SNe 2005P and 2008ge are very similar. Although SN 2005P has strong emission at the wavelengths corresponding to the [Fe II] features, they are not as strong as in SN 2008ge. Additionally, the centroid of the red peak is offset from that of SN 2008ge. To further examine these differences, we produce a residual spectrum in the same manner as above and present

the result in the bottom panel of Figure 6. The residual spectrum has strong positive residuals – but not as strong as for SN 2002cx – at the wavelengths of [Fe II], suggesting that the SN 2008ge has stronger [Fe II] emission than SN 2005P, which in turn has stronger emission than SN 2002cx. The residual spectrum also has a strong negative residual at the Ca II NIR triplet.

From the residual spectrum, it is clear that the offset in the centroid of the red peak of the 7300 Å feature for SN 2005P and 2008ge is the result of weaker [Fe II] emission and stronger [Ca II]  $\lambda\lambda 7291, 7324$  in SN 2005P. The [Ca II] lines are easily identified as strong negative residuals in the residual spectrum.

Nebular lines have recently been used to probe the asymmetry of SNe Ia (Maeda et al. 2010). In particular, the [Fe II]  $\lambda 7155$  and [Ni II]  $\lambda 7378$  are excellent probes of the deflagration stage of the SN explosion. For the emission feature at 7400 Å, it is unclear what the relative contributions of [Ni II]  $\lambda 7378$ , [Fe II]  $\lambda\lambda 7388, 7453$ , and [Ca II]  $\lambda\lambda 7291, 7324$  are; it is therefore difficult to assess a velocity shift for any of these features. However, the feature at  $\sim 7200$  Å is almost exclusively [Fe II]  $\lambda 7155$ , with some contribution from [Fe II]  $\lambda 7171$ . Fitting a Gaussian to this line in both the normal and SN 2002cx-subtracted spectra, we find velocity offsets (assuming that the line is dominated by [Fe II]  $\lambda 7155$ ) of +900 and +1350 km s<sup>-1</sup>, respectively.

Maeda et al. (2010) found offsets between about -3000 and +3000 km s<sup>-1</sup>. SNe 2002cx and 2005hk both had velocity offsets (as measured by the [Ca II] lines) of  $\sim +300$  km s<sup>-1</sup> (Sahu et al. 2008). SN 2005hk had relatively low polarization at maximum light, indicating a small asymmetry (Chornock et al. 2006). It is unclear if the shift of forbidden lines in SN 2008ge is indicative of asymmetry, and furthermore, if such an asymmetry translates into a different late-time spectrum than other members of the class.

#### 4. DISCUSSION & CONCLUSIONS

##### 4.1. The Progenitor of SN 2008ge

The progenitors of SN 2002cx-like objects have recently been a subject of debate (F09; Foley et al. 2010a; Valenti et al. 2009). Fortunately, the position of SN 2008ge, which we have shown to be a spectroscopic member of the class, was imaged by *HST* before the star exploded. Since SN 2008ge is a very nearby object, these images constrain the luminosity, and therefore mass, of the progenitor star and any possible binary companion.

We have pinpointed the location of the SN in pre-explosion images that indicate that the progenitor star (or system) had  $M_V \geq -6.7$  mag ( $3\sigma$  limit), corresponding to a mass limit of  $M_{\text{init}} \lesssim 85M_\odot$  for a star on the main sequence and  $M_{\text{init}} \lesssim 12M_\odot$  for horizontal or red-giant branch star. The same limits apply to any potential binary companion.

Since there is no indication of H or He in the spectrum of SN 2008ge, its progenitor was likely a highly evolved star such as a WD or Wolf-Rayet star. Our limits are only able to rule out the most-luminous Wolf-Rayet stars, corresponding to stars with initial masses of  $\gtrsim 65M_\odot$  (Crowther 2007, and references therein), while the minimum initial mass to reach a Wolf-Rayet stage appears to be  $\sim 25M_\odot$ .

Observations of the host galaxy also present indirect constraints on the progenitor. The spectrum of the galaxy has no emission lines, and is well fit by a single-stellar population model with an age of 9.5 Gyr. The surface-brightness profile of the galaxy is extremely smooth, indicating that there are no exceptionally luminous stars or large star clusters near the position of SN 2008ge. Limits from *IRAS* place the SFR below  $7.2 \times 10^{-3} M_\odot \text{ year}^{-1}$ . Wolf-Rayet stars are very young, and they are generally associated with high SFRs and spatially coincident with star clusters and H II regions (e.g., Hadfield et al. 2005) that should have been detected in the *HST* images if present. We see no indication of (1) narrow emission lines in the SN spectrum, (2) narrow emission lines in the host-galaxy spectrum, (3) far-infrared emission from the host galaxy, (4) H I 21 cm emission from the host galaxy, (5) any luminous source at the position of the SN, or (6) any luminous source within the *HST* field of view. This evidence greatly constrains the environment of the progenitor of SN 2008ge and is highly suggestive that it was not a massive star of any sort.

The pre-explosion imaging combined with a lack of hydrogen in the SN spectrum rules out all stars except for some Wolf-Rayet stars, WDs, and relatively low-mass binary stars. The additional observations of the host-galaxy make a Wolf-Rayet progenitor unlikely. A binary system where one star has transferred its hydrogen (and possibly helium) envelope to its companion before exploding (possibly through electron capture) is possible. A WD progenitor is also consistent with all observations. But if the progenitor of SN 2008ge was a WD, then we expect any binary companion to have a mass less than the maximum mass that still allows WD formation (otherwise the progenitor of SN 2008ge would have exploded as a SN before reaching the WD stage). From open clusters, we see that some stars with  $M_{\text{init}} = 6.5M_\odot$  will become WDs (Ferrario et al. 2005). For all stages of stellar evolution, a  $6.5M_\odot$  star would be below our detection limit; therefore, this is also consistent with our observations.

##### 4.2. SN 2008ge: The Supernova

Unfortunately, SN 2008ge was detected long after maximum brightness, precluding detailed early-time observations. Luckily, we were able to recover the SN on our pre-detection images. With these images, we constructed a light curve that included maximum light.

SN 2008ge peaked at  $M_V \approx -17.4$  mag, similar to the peak absolute magnitude of SNe 2002cx and 2005hk, but fainter than typical SNe Ia. Its *V*-band light curve declines very slowly, with  $\Delta m_{15}(V) \approx 0.34$  mag. The similar peak magnitudes and ejecta velocity of SNe 2002cx and 2008ge and drastically different decline rates can be explained if both objects generated a similar amount of  $^{56}\text{Ni}$ , but SN 2008ge had more massive ejecta. More detailed modeling, which is beyond the scope of this paper, is required to determine the exact physical parameters of these objects.

The late-time spectra of SNe provide a glimpse at the inner regions of the SN ejecta. Although most SNe become “nebular” by 200 d after maximum, this is clearly not the case for SNe 2002cx and 2005hk, which had P-Cygni lines at this time, indicating a photosphere

(Jha et al. 2006; Sahu et al. 2008). The late-time spectrum of SN 2008ge does not clearly show any P-Cygni lines. However, the overall shapes of the spectra of SNe 2002cx and 2008ge are very similar, and it is likely that the composition of their ejecta are very similar, but SN 2008ge simply has a larger velocity.

The nebular spectra of SNe Ia are dominated by forbidden Fe transitions while SNe Ic are dominated by Mg I], [O I], [Ca II], and Ca II features. The detection of strong [Fe II] emission at late times is a further indication that SN 2008ge generated a significant amount of  $^{56}\text{Ni}$  (which eventually decayed to Fe).

There is a significant offset in one of the forbidden Fe lines that can not be explained by simple galactic motion. This offset may be indicative of an asymmetric explosion (at least in the core) that could perhaps explain the spectral differences between SN 2008ge and other members of this class at late times.

#### 4.3. SN 2008ge in the Context of the Class of SN 2002cx-like Objects

Valenti et al. (2009) suggested that SN 2002cx-like objects, and particularly SN 2008ha, have massive progenitors. F09 also presented massive progenitors as one of many possibilities for SN 2002cx-like objects in general, and SN 2008ha in particular (although Foley et al. 2010a showed that SN 2008ha likely had a WD progenitor). Since it was unlikely that SN 2008ge had a Wolf-Rayet progenitor and since fallback SNe require a star with  $M_{\text{init}} \gtrsim 25M_{\odot}$  (Fryer 1999), we can rule out the fallback scenario. The electron capture of a star in a binary system that has lost its outer envelopes to a binary companion is still viable for SN 2008ge; however, other observations make this an unlikely path for the entire class of SN 2002cx-like objects (F09). Of all models presented by F09, only one is consistent with all observations: a deflagration of a WD, where some SN 2002cx-like events are possibly a full deflagration of a Chandrasekhar mass WD, some are possibly full deflagrations of a sub-Chandrasekhar mass WD, and some are a partial deflagration of a WD that does not fully disrupt the star. Recent numerical models of sub-Chandrasekhar WD detonations have been successful at producing light curves and spectra somewhat similar to normal SNe Ia (Fink et al. 2010; Pakmor et al. 2010; Sim et al. 2010; van Kerkwijk et al. 2010). These models only explore progenitors with relatively large total mass, and additional models at lower total mass may reproduce the features of this class. (In fact, as the total mass decreases, the models predict that the SN will fall off of the Phillips relationship similar to SN 2002cx-like objects; Sim et al. 2010.) Whatever is the correct model, it must explain the strong [Fe II] lines in the late-time spectra of SN 2008ge, which suggests that a significant fraction of its ejecta is Fe, likely the result of radioactive decay of  $^{56}\text{Ni}$ , although a significant portion of the Fe may come from  $^{54}\text{Fe}$  or even possibly directly synthesized  $^{56}\text{Fe}$ .

The detection of He (but not H) in SN 2007J (F09) is a further constraint for the progenitors of these objects, indicating that a significant amount of He is present in at least some of the progenitor systems. The He may come from the WD itself or from a binary companion, requiring that the companion be a He star.

The host-galaxy morphology distribution of this class

of objects is heavily skewed to late-type galaxies, with only SN 2008ge hosted by an early-type galaxy (F09). Although this distribution is consistent with SN 1991T-like SNe Ia (F09), which must have WD progenitors, it is an indication that a significant number of progenitor systems must be relatively young.

With the constraint on the progenitor of SN 2008ge, we have a crucial limit on the progenitors of the SN 2002cx subclass of SNe. Future observations of nearby SNe with deep pre-explosion imaging may further constrain the progenitors of these objects.

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